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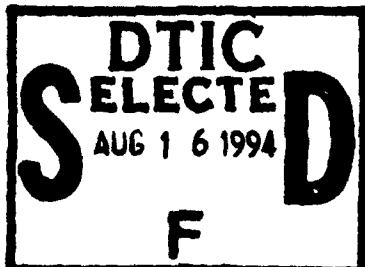
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Ice Formation in an Estuarian Salt Marsh, Alaska

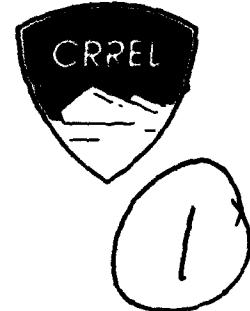
Susan Taylor, Charles H. Racine, Charles M. Collins
and Elizabeth Gordon

June 1994



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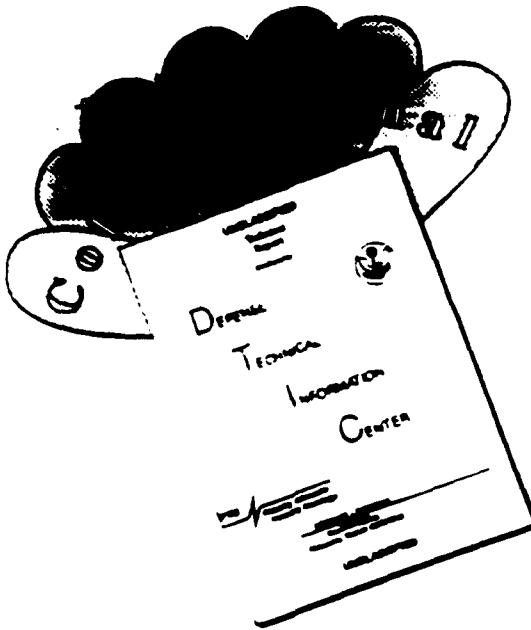
Abstract

An extensive ice sheet builds up during the winter in a salt marsh complex at the mouth of Eagle River near Anchorage, Alaska. To clarify how snow accumulation, periodic tidal flooding, and freshwater flow contribute to the ice cover, ice cores were taken along a transect beginning at a deep pond along the edge of the salt marsh and transversing marsh, shallow pond, and mudflat areas. Ice structure, ice salinity, ice thickness, and the presence or absence of sediment bands in the ice are described and were found to change markedly along the transect.

For conversion of SI metric units to U.S./British customary units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-89a, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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Special Report 94-17



**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

Ice Formation in an Estuarian Salt Marsh, Alaska

Susan Taylor, Charles H. Racine, Charles M. Collins
and Elizabeth Gordon

June 1994

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PREFACE

This report was prepared by Susan Taylor, Research Physical Scientist, and Charles H. Racine, Research Physical Ecologist; Charles Collins, Research Physical Scientist; and Elizabeth Gordon, Physical Science Aide, of the Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

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Ice Formation in an Estuarine Salt Marsh, Alaska

SUSAN TAYLOR, CHARLES H. RACINE, CHARLES M. COLLINS and ELIZABETH GORDON

INTRODUCTION

Eagle River Flats (ERF or the Flats) is an 865-hectare (2162-acre) estuarine salt marsh located off the Knik Arm of Cook Inlet in Alaska (Fig. 1). About 2.8 km wide near the coast, this salt marsh contains the Eagle River, its distributaries and levees, and a number of vegetation zones (Fig. 1 and 2). The zones change from bare or vegetated mudflats, to sedge and bulrush marshes and shallow ponds, to meter-deep ponds as one approaches the periphery of the flats.

Since the 1940s, Eagle River Flats has been used by the Army as an artillery range. The death of large numbers of migratory birds indicated that there were serious contamination problems at ERF; Racine et al. (1992, 1993) determined that white phosphorus, a component of smoke munitions, was responsible.

As part of a study examining the fate and persistence of white phosphorus (P_4), we wanted to know:

- if the ice cover that formed at ERF incorporated or redistributed the contaminated sediments;
- the amount of sediment contained in the ice and possibly deposited on the flats in the spring; and
- the thickness of the ice at different locations.

The last information was needed to ensure that winter-time artillery practice would not break through the ice and redistribute the P_4 .

Most studies of ice formation in northern wetlands have been conducted along the east coast of Canada and the United States. Dionne (1989) has studied the effect of ice on marshes and estuaries in Quebec. Here, ice forms in open water and is subjected to large tidal fluctuations. The surface topography of the estuaries is affected when pieces of ice and frozen underlying sediment are pulled up and deposited elsewhere.

Meese et al. (1987) described estuarine ice from New Hampshire's Great Bay. The water in this estuary is predominantly saline and forms frazil and congelation ice. The ice is generally free floating and subjected to tidal action. Sediments are found between the crystal platelets of the ice and are thought to be incorporated as the ice grows into water containing suspended sediments. These processes were unlike those observed at ERF.

The Flats are separated from Knik Arm by a mud-faced shore that slopes toward Knik Arm and that is part of a mudflat zone with deep distributary channels. This zone extends upriver along Eagle River (Fig. 1). Elevations in the mudflats are 4.5–5.1 m and decrease toward the pond-marsh zone, where elevations are 4.4–4.6 m. Flooding of the flats occurs when water enters and overtops the channel of the Eagle River and its distributaries. In the summer, flooding can also occur when a high river discharge is dammed by a moderately high tide, causing fresh water to flood the Flats. A pressure transducer set up in pond C during the summer measured 11 rapid rises in pond level between 16 Aug and 21 Sept 1990 (Racine et al. 1992), which occurred whenever the tides were greater than 9.1 m (30 ft). The summer flood waters were observed to drain within a few hours after the high tide.

From October to March, an extensive ice sheet builds up in ERF (Fig. 3). The ice sheet covers areas such as mudflats and levees that have standing water only when flooded by summer high tides. In the winter, tidal flooding helps build the ice sheet by flowing over frozen ground or ice and freezing to form new ice layers. Occasionally, a high tide may flood all or most of the Flats, but usually flooding spreads out from the distributary channels as lobes or splays of water that build up an ice layer over a limited area. The thickness of these layers will depend on the height of the tide, the local terrain features, and the presence or absence

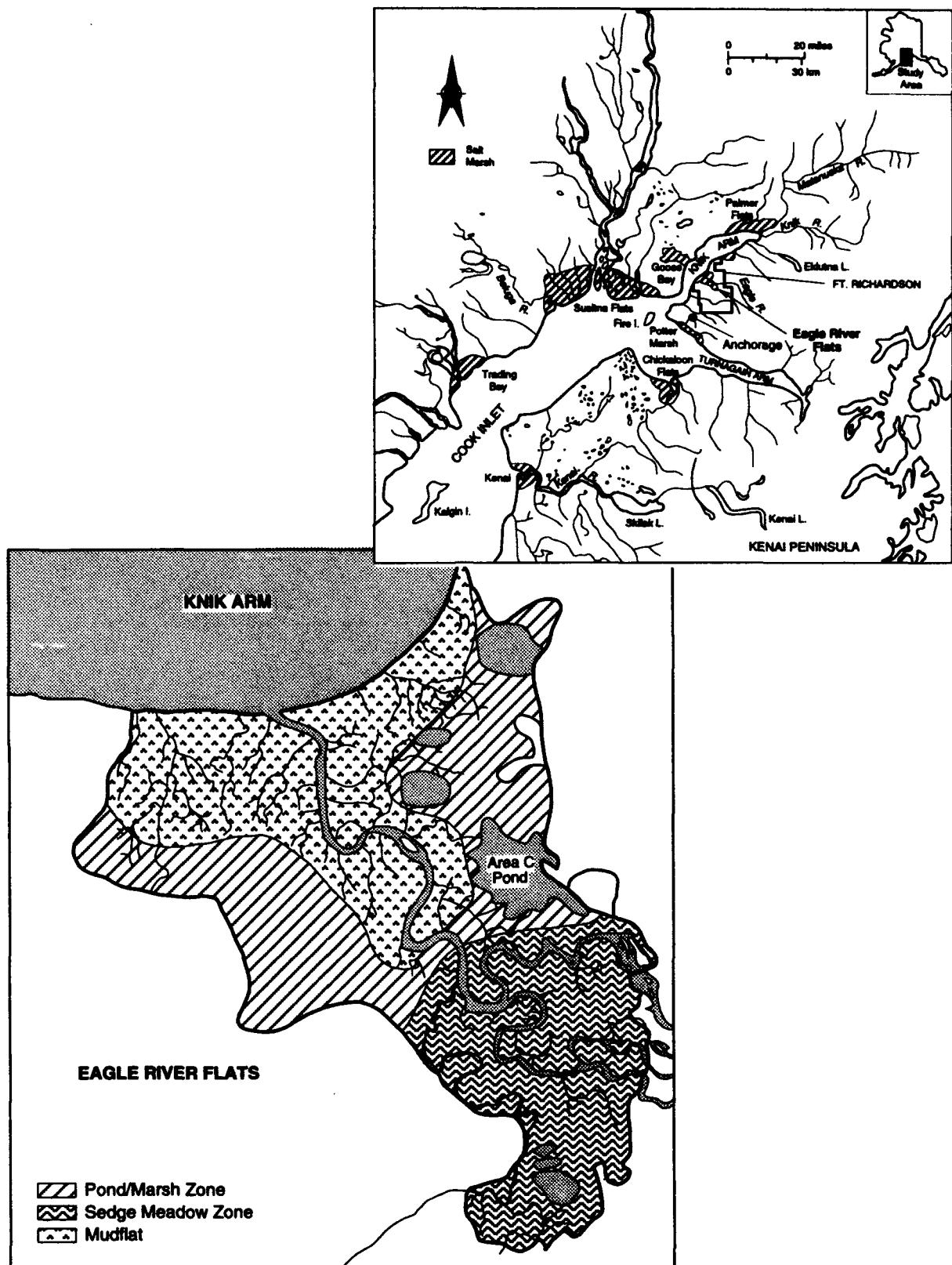


Figure 1. Location of Eagle River Flats in relation to Cook Inlet and the state of Alaska. Grey areas are permanent ponds. The extent of the major vegetation zones are marked on the map.

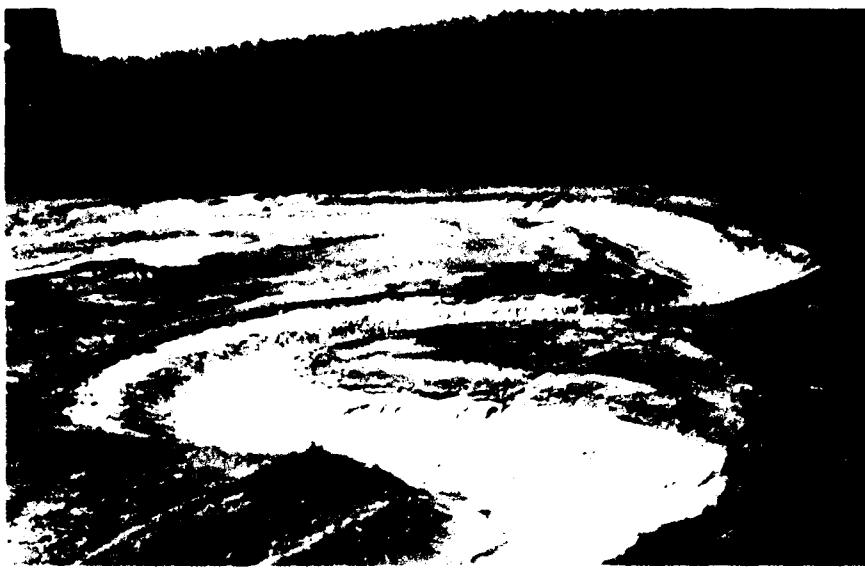


Figure 2. The Eagle River in early spring showing vegetated mudflats, sedge marsh, and a pond.



Figure 3. Winter view of Eagle River. Note grey areas in the snow cover where selective flooding has saturated the snow.

of snow. When snow is present, the tidal water either partially or totally saturates the snow and freezes to form snow ice, which is bubbly, white, and less dense than clear congelation ice.

No information was found on ice formation in a salt marsh similar to Eagle River Flats, so to describe the processes primarily responsible for the ice cover at ERF, ice cores and any attached frozen sediments were obtained in February 1991 and January 1992. This paper describes the structure of selected ice cores and, from these, hypothesizes

about the sequence of events that formed the ice. To interpret the cores we assume that salinity values over 1‰ indicate tidal flooding and that sediment settles out from flood waters to form a layer that marks the base of the flooding event.

MATERIALS AND METHODS

Three-inch-diameter (7.6-cm) ice-sediment cores were obtained using a SIPRE coring auger. Different landform and vegetative zones were

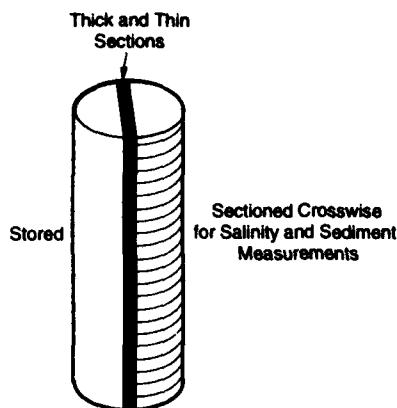


Figure 4. How the ice cores were cut and sampled.

sampled by taking cores along transects running from the pond at the periphery of our study area, through a sedge and/or bulrush marsh, to the shallow pond and the mudflat beyond.

The cores were kept frozen and shipped back to CRREL for laboratory analysis. Each core was cut in half lengthwise, and one half was bagged and saved. A 1-cm-thick longitudinal section was cut from the central section of the other half, and thick and thin sections of the core were prepared following the methods of Weeks and Gow (1978). The remaining part was then cut crosswise into 1-cm-thick pieces that were analyzed for salinity and sediment content as a function of depth (Fig. 4).

A Selectro Mark analyzer conductivity meter, calibrated using standards, was used to determine the salinity for all cores except core 31, where a Dionex ion chromatograph was used. After evaporating the water, the weight of the solids (sediments, salts, and vegetation) was obtained with a Mettler balance. The weight of the salt was calculated from the salinity and subtracted to obtain the sediment weight. With the exception of a few samples, there was little or no vegetation, and its contribution to the sediment weight is ignored.

Six cores collected in 1991 were studied. Three cores were from a transect running from the pond at area C to the adjacent sedge marsh (60, 62, and 178), two were from the pond in area C (27 and 31), and one was from the mudflat (185) (Fig. 5). The sediment portion of the core taken from the sedge marsh (178) was thick sectioned and X-rayed to clarify the sediment structure and the nature of the ice-sediment boundary.

In 1992, nine cores were taken at 50-m intervals along a single E-W transect running through a pond (E4, E3), marsh (E2, 200, 202), shallow pond (204, 205, 206), and mudflat (207) (Fig. 5). These,

too, were sectioned, and the salinity and sediment contents were determined.

The salinity of the ice depends upon many variables, one of which is the salinity of the tidal water. We looked for references giving the salinity of Knik Arm; unfortunately, only the salinity of upper Cook Inlet has been measured and that only infrequently. It was 10‰ in July (Rosenberg et al. 1967) and about 18‰ in May 1968 (Kinney et al. 1970); the latter measurement was made before spring runoff from the rivers added fresh water to Cook Inlet. Salinity has not been measured during the winter, but it is probably 18‰ or higher. The amount of suspended sediment in Knik Arm also varies seasonally, ranging from 350 to over 1000 mg/l from May to July.

RESULTS AND DISCUSSION

Pond core—1991

Pond areas along the perimeter of the Flats have water depths of up to half a meter under ice that is 40 to 70 cm thick. Ice from the pond in area C is represented by core 31, which is 66 cm long and from the top down has 15 cm cloudy ice, 15 cm orange ice (see *Sediments* section), 6 cm sediment bands and ice, 8 cm cloudy ice, and 22 cm clear ice.

The bottom 30 cm of core 31 (Fig. 6) is interpreted to be frozen pond water. Thin sections show an 8-cm section of congelation ice overlying a 10-cm section that appears to be a single crystal of ice overlying 10 cm of ice consisting of a few large crystals. We think that after the initial formation of congelation ice, an inflow of cold water under the ice formed the single-crystal horizon. This cold water carried sediment that is found at the interface with the congelation ice and in pockets within the ice crystal. The pockets formed when the sediment was excluded from the ice lattice during freezing. The pond water then resumed freezing below this layer.

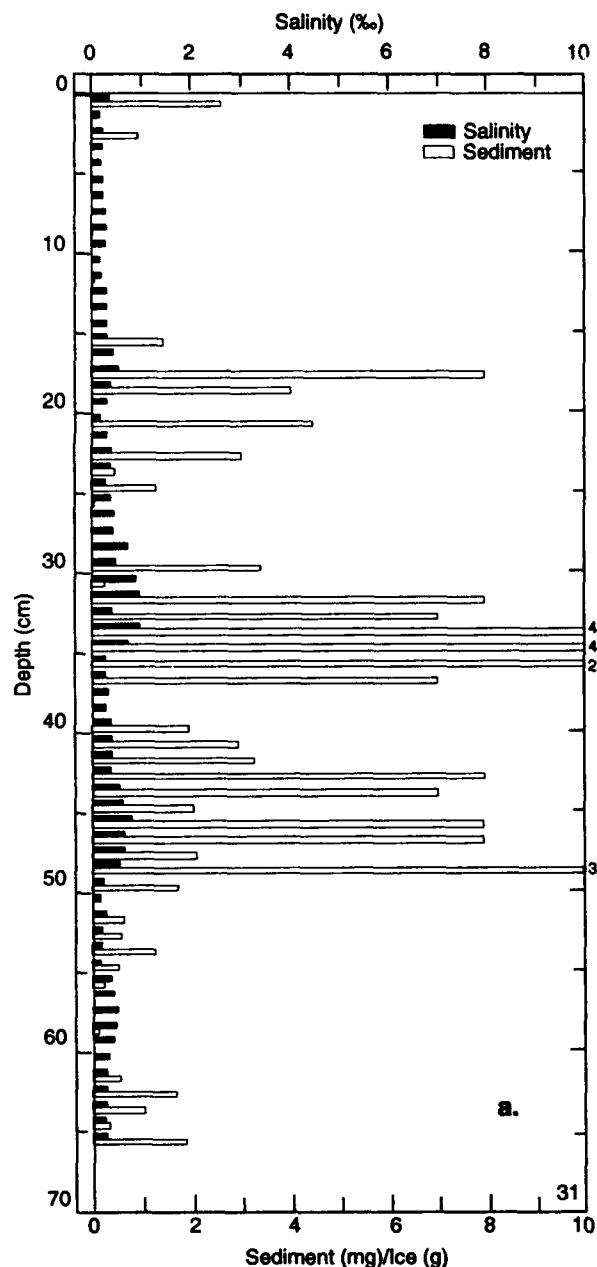
The central section of the core, from 30–36 cm, has thin layers of congelation ice with high sediment contents (40–50 mg of sediment/g of ice). These layers are thought to have formed from a series of flooding events, one of which may also have flowed under the ice and formed the single-crystal ice.

The top 30 cm of the core consists of ice with grains of various sizes and crystal orientations. We are interpreting this section as snow ice although it does not display the similarly sized grains seen in "standard" recrystallized, wetted snow. The velocity and/or the temperature of the water wetting the snow probably determines the equidimensional nature of the snow ice.



Figure 5. Aerial infrared image of area C showing the ponds (black), shallow pond areas (blue), sedge marsh (brown), and mudflats (greenish brown). Eagle River Flats is an Army artillery impact range, which is evident from the many craters that pepper the surface.

The overall salinity of core 31 is less than 1‰, but there appears to be a cyclic nature to the salinity in both core 31 and core 27, another core from this pond. The spacing between the peaks in both cores is about 15 cm (Fig. 7). Although the peaks are not synchronous and there are three peaks in core 27 and four in core 31, the presence and cyclicity of these peaks suggest that some tidal water is reaching the pond.



Marsh core—1991

Core 178, from a sedge marsh in area C, consists from the top down of 19 cm cloudy ice, 4 cm clear ice, 17 cm of ice containing vegetation, and 30 cm of frozen black silt. As the salinity ranges from 2.5 to 6‰ in the bottom 17 cm of the core, tidal flooding probably contributed water to this ice. From the number of sediment layers present in the bottom 17 cm of ice, four flooding events are thought to have occurred. The first provided the water for the first 4 cm of ice. The second deposited the well-defined horizontal sediment layer 4 cm above the ice—

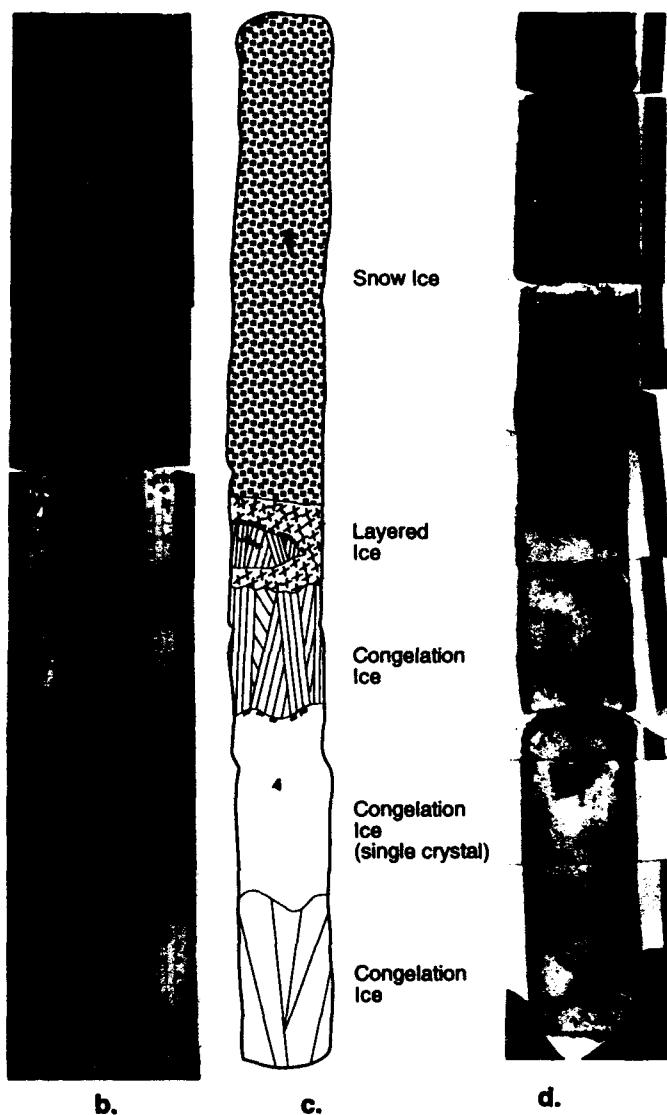


Figure 6. Core 31: (a) salinity and sediment content of the core, (b) thin section of the core, (c) our interpretation of how the ice formed, and (d) thick section.

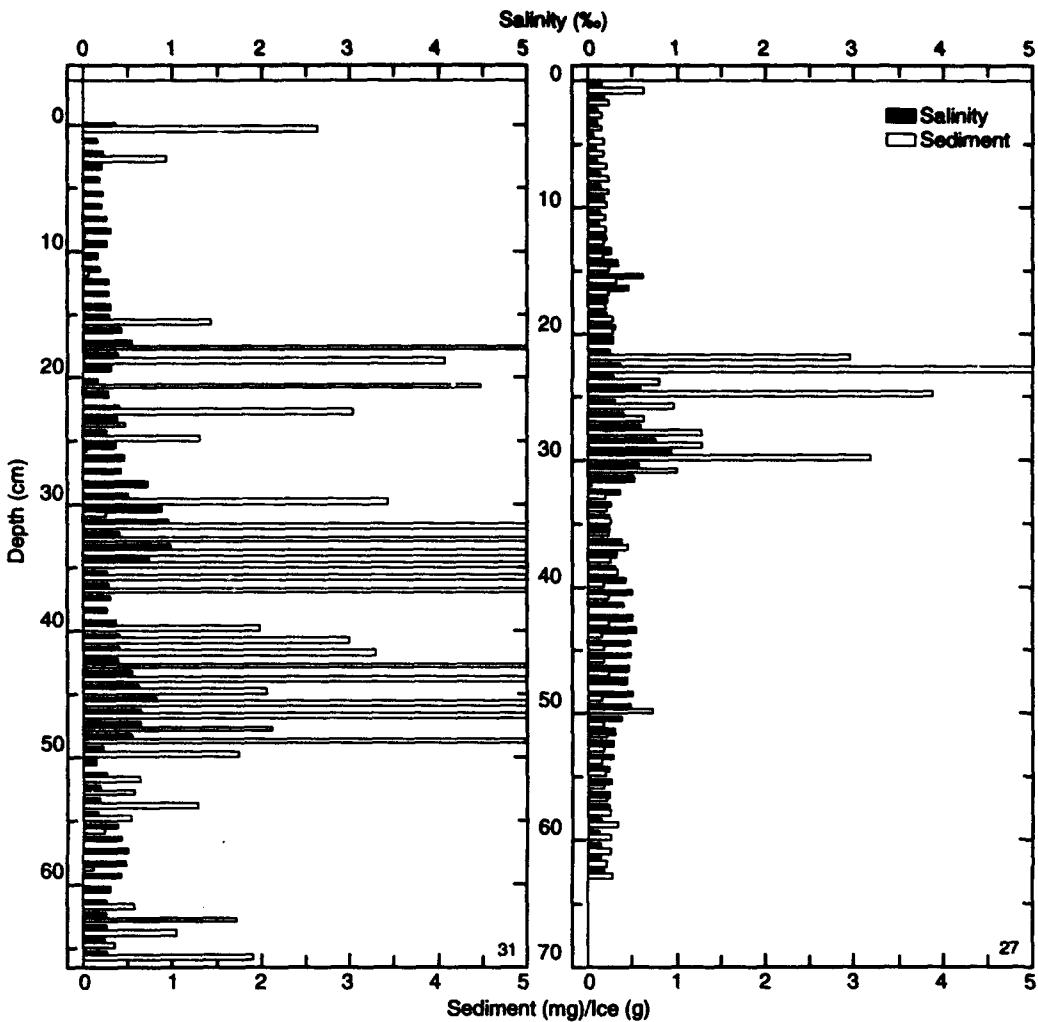


Figure 7. Comparison of the salinity and sediment profiles of cores 31 and 27. These cores were collected on the same day from the pond in area C. The tops of the records have been offset to reflect the difference in surface elevation measured at the two sites.

sediment boundary (Fig. 8). The base of the third flooding event is 10 cm from the ice-sediment boundary (where the core broke), and the base of the fourth is at 16 cm from the boundary where the vegetation, which until then had been upright, becomes incorporated horizontally into the ice (Fig. 9). Because sediment bands correlate with peaks in salinity (Fig. 8), most of the sediment is thought to be deposited during tidal flooding.

Above the 17-cm horizon, there are 4 cm of fresh congelation ice capped by a 0.5-cm layer of clear ice. This thin layer is interpreted as a standing surface where the ice was exposed to the elements (sun, rain, etc.) before being covered by snow. On top of the congelation ice, and making up the rest of the core, is snow ice. It has a salinity of less than

1‰, except at a sediment layer 21 cm from the ice-sediment boundary and at 30 cm, where the core broke as it was collected. These two horizons may be tidal flooding events. The snow ice has a section of finer-grained crystals under a coarser-grained section (Fig. 8).

The ice-sediment boundary is obscured by emerging vegetation and sediment bands. Fig. 10 is an X-ray of the sediment section, which shows a large amount of old vegetation within the sediment (light gray areas) and the ice-sediment boundary. Ice needles can be seen growing into the sediment, and the interfingering of ice and mud produces a strong bond. When the cores were drilled they tended to break along salinity-sediment bands, not at the ice-sediment boundary.

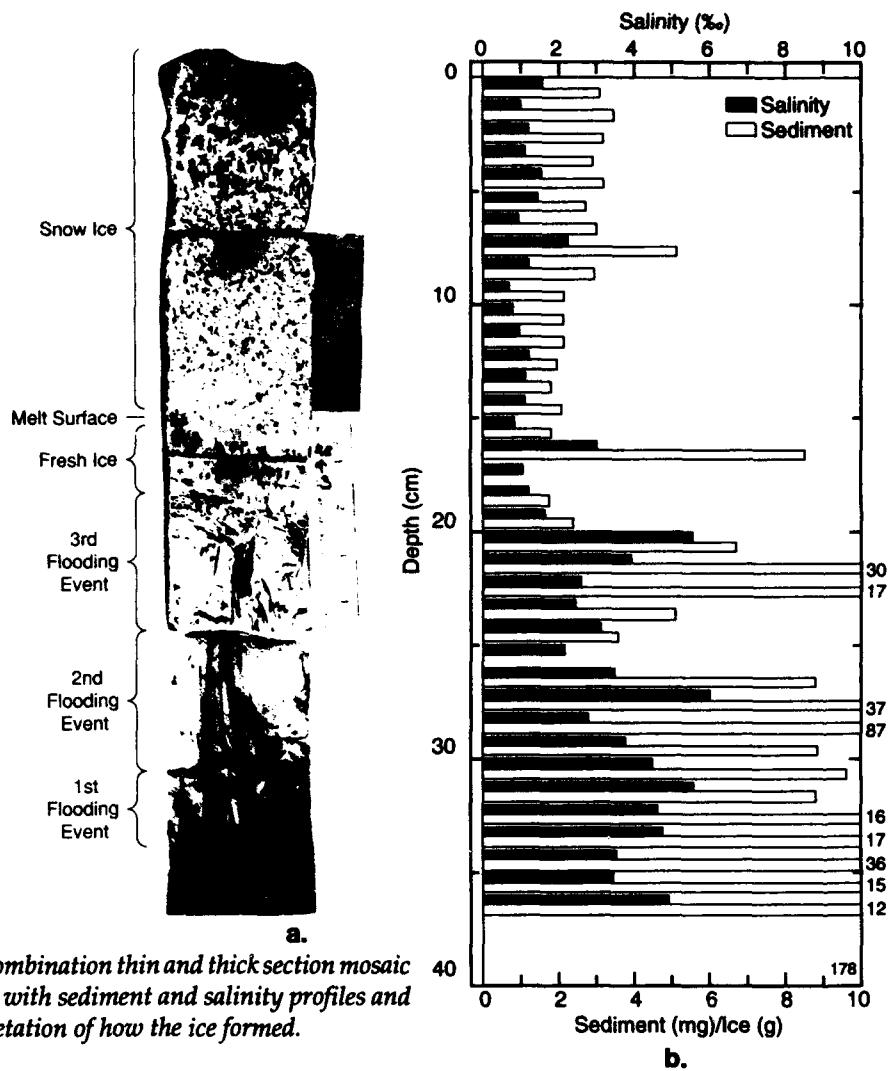


Figure 8. Combination thin and thick section mosaic of core 178, with sediment and salinity profiles and our interpretation of how the ice formed.



Figure 9. Thick section of bottom portion of core 178 showing how the vegetation goes from being vertically to horizontally incorporated (\leftarrow) within the ice.

Mudflat core—1991

Core 185 was collected from a mudflat area (Fig. 5) and consisted of 45 cm of ice (sediment bands at 15, 17, and 20 cm) overlying 20 cm of partially frozen silt. Unlike the other cores that were sectioned at 1-cm intervals, this core had such distinct bands and crystal structure that we used them as a guide to sampling (Fig. 10). As this area is dry during the summer, the ice formed from the ground up.

The bottom 20 cm of core is congelation ice, of varying coarseness, and has salinity values between 1 and 3.5‰. Four separate flooding events (Fig. 11) can be inferred if we assume that sediment bands mark the base of each overflow and that, in turn, each overflow event froze to form ice. In the laboratory, a suspension of ERF sediment in water settles in about 10 minutes (most of the sediment on the bottom, murky water on top) with complete separation in less than 2 hours (clear water over sediment). The tops of layers 2 and 4 have a thin,

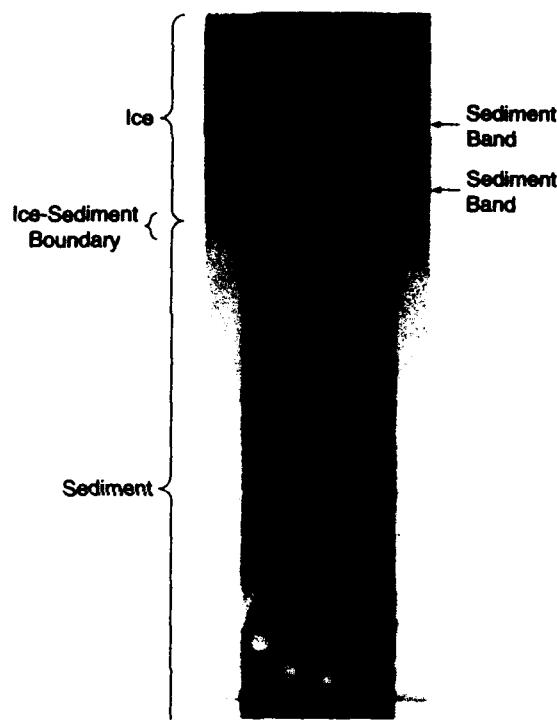


Figure 10. X-ray of frozen sediment section of core 178 showing the ice-sediment boundary. The interface is characterized by ice needles growing into the sediment. Large amounts of vegetation, which appear light grey and include the three fingerprint-like marks near the base of the core, are incorporated within the sediments.

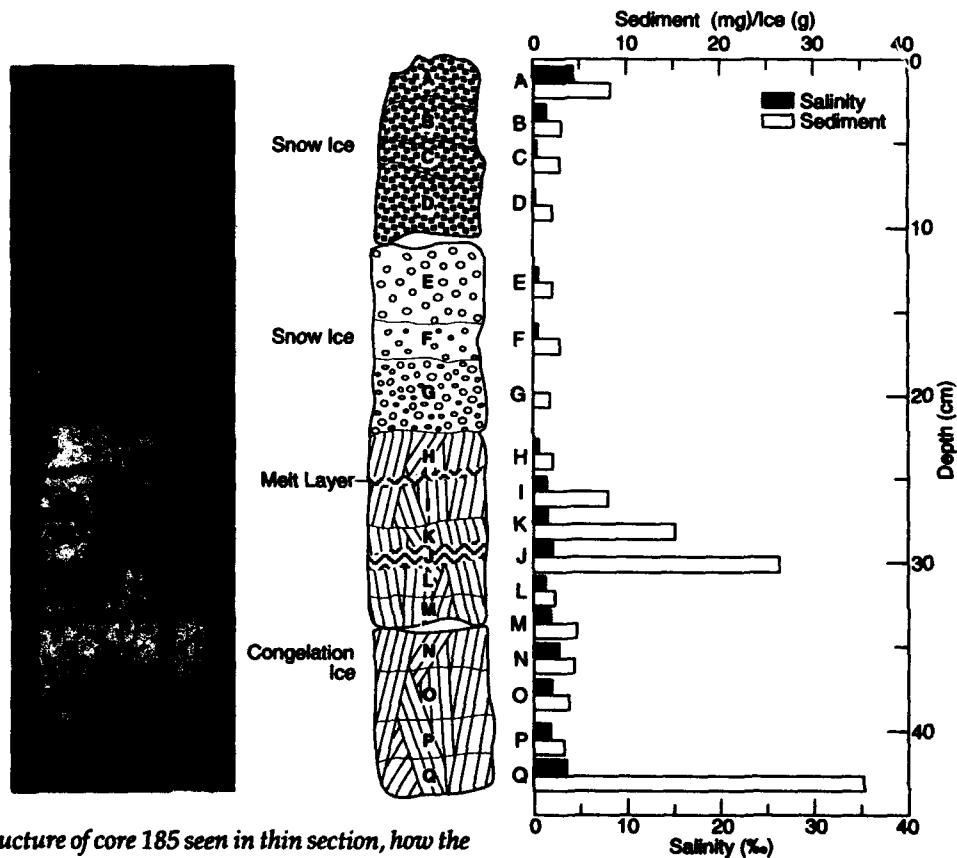


Figure 11. The ice structure of core 185 seen in thin section, how the core was sampled for salinity and sediment content, and the results of the samples.

clear ice layer, which is interpreted as a rain or melt event that occurred when that ice was exposed at the surface.

This bottom 20-cm section of ice is capped by a 2-cm layer of freshwater congelation ice and then by 23 cm of relatively fresh snow ice. The snow ice varies from large, equidimensional crystals at the base of the section to smaller grains of random crystal orientation at the top. Because the salinity and sediment contents increase at the top of the section, the top of the snow ice appears to have been flooded by tidal water.

Description of cores along the 1991 transect

Three cores were analyzed from a February 1991 transect that went across the pond in area C to the sedge marsh. The ice thickness decreases as one goes from the eastern periphery of pond C to the marsh (Fig. 12). The salinity and sediment content of the ice vs. depth for these cores (60, 62, and 178) show a correlation between increases in salinity and increases in sediment concentration (Fig. 13). Note that the top of each ice core is set relative to the ice surface elevation along the transect. The higher surface elevation of the pond suggests that local runoff is contributing to the ice thick-



Figure 12. Cores 60, 62, and 178. The lines show the ice-sediment boundary.

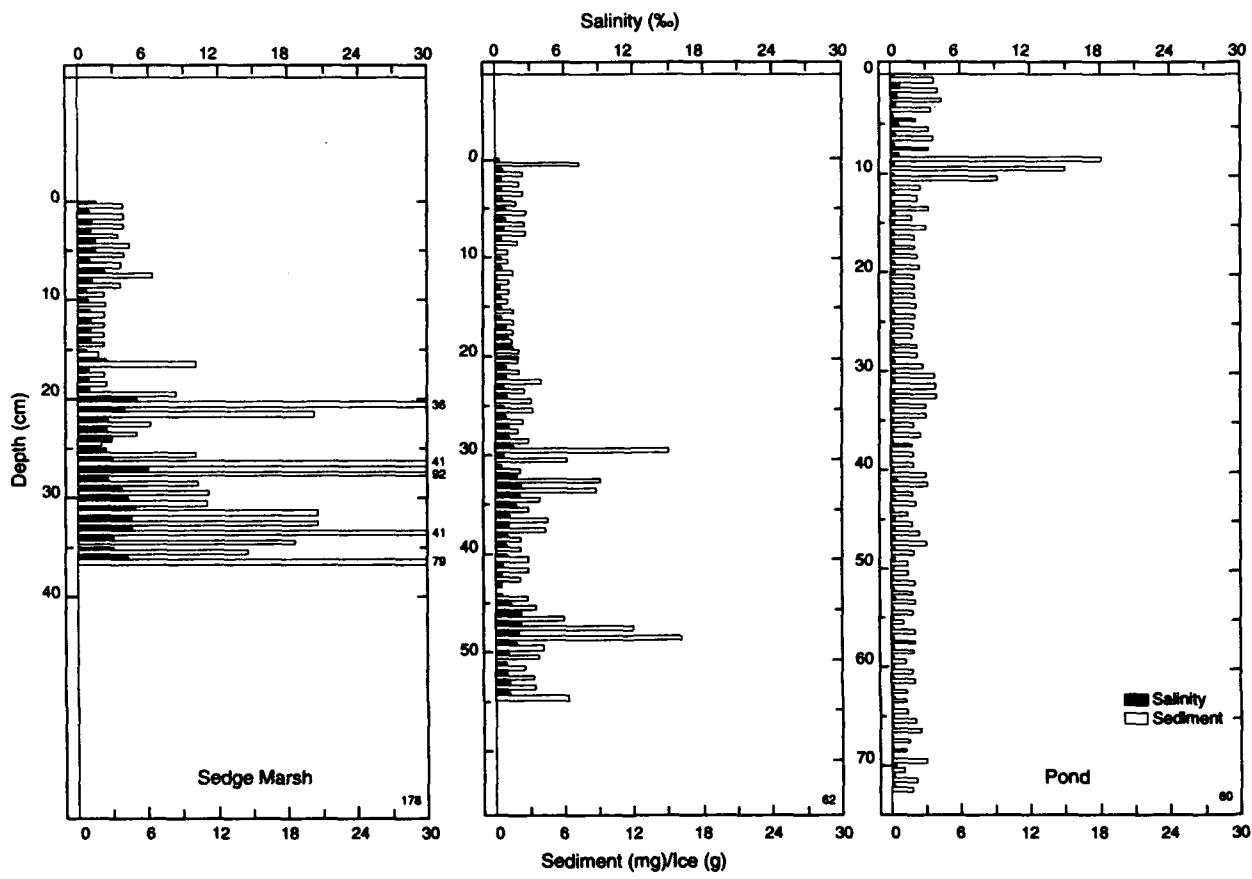


Figure 13. Salinity and sediment profiles for cores 60, 62, and 178. The offset of the profiles reflects the difference in the surface elevation among the sites.

ness. Figure 13 also shows that both the number and the magnitude of salinity and sediment peaks of each core decrease with the core's proximity to the eastern edge of the Flats. The decrease indicates that only the highest tides are reaching the shore or that fresh water from the land is diluting the saltwater signature. The salinity-sediment peaks at 41–42 cm (core 60), and 30–31 or 34–35 cm (core 62), may have been formed from the same flooding event.

Description of cores along the 1992 transect

In January 1992, a series of cores were collected along a 400-m transect from the pond in area C, across a mixed bulrush-sedge marsh and onto the mudflat (Fig. 5 and 14). The cores are characterized by congelation ice overlain by very porous snow ice (Fig. 15) and are about half the length of the 1991 cores.

Like the 1991 cores, the 1992 cores of pond and

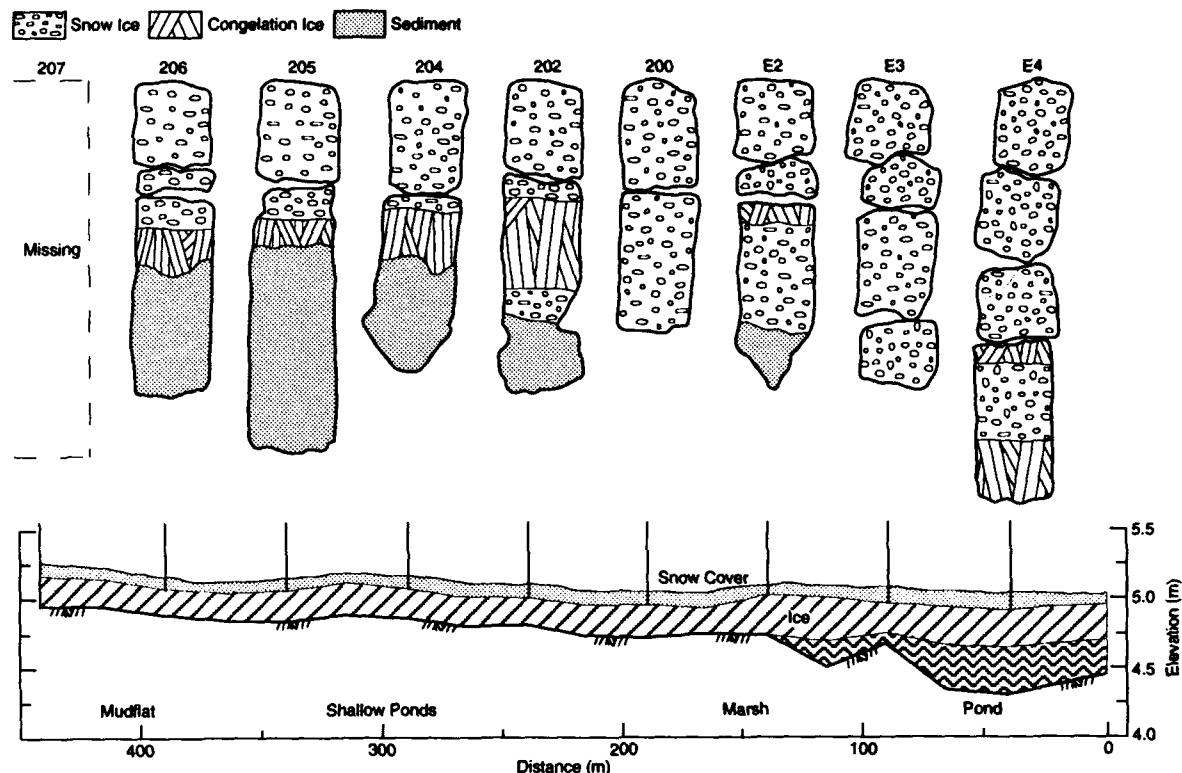
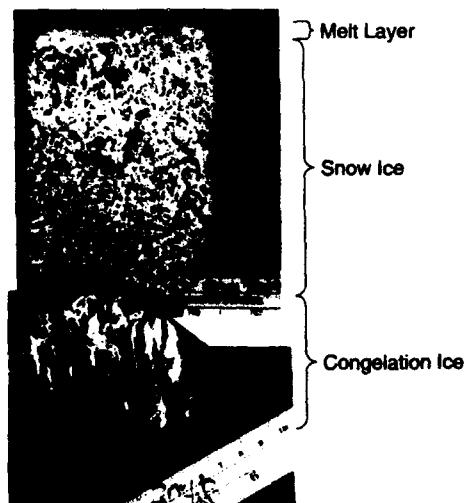


Figure 14. Cross section showing the sediment, ice, and snow surface elevations along the E-W transect in area C. Drawings of the cores, showing length and prominent features such as bubble or sediment bands, are above the cross-section location of each sample site.

Figure 15. Thin section of core 204 showing congelation ice at the base and snow ice on the top. The clear ice cap at the top of the core is interpreted as a melt layer.



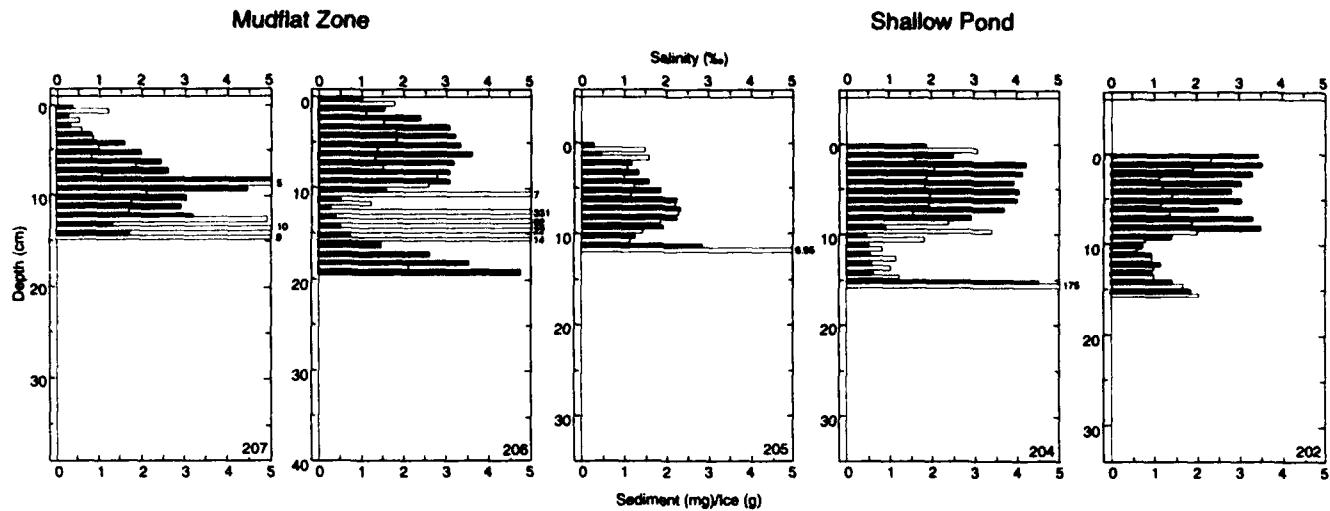


Figure 16. Sediment and salinity profiles of the cores taken along the 1992 E-W transect.

marsh areas are less saline and have less sediment than those from the shallow ponds and mudflat areas. In addition, sediment spikes are associated with an increase in salinity. Core 206 is an exception.

Unlike the 1991 cores, the congelation ice generally has a lower salt content than the overlying snow ice (Fig. 16). The 1992 cores have no distinct ice or sediment layers, and the average amount of sediment in these cores is also lower (2 mg of sediment/g of ice, Fig. 16, as compared with 4 mg/g for the same area of the pond in 1991).

Tidal records show that in 1990–91 there were three tides that were over 10 m in October and early November (Fig. 17). The winter had below-average snowfall in October, January, and February, and 50% more snow in November and December as compared with an average derived

from the 1962–1992 snow record. In 1991–92, the highest tides, greater than 10 m, occurred in January and February (Fig. 17), and there was 50–100% more snow throughout the winter than the 30-year average. The absence of ice and sediment layers in 1992 is attributed to the large amount of snow that fell at ERF from October through March and the fact that the highest tides occurred later in the winter after a lot of snow had accumulated. We think the flood waters are slowed and wicked up by the snow.

Sediments

Most of the sediments are gray, clay-sized rock flour; 98% is less than 0.1 mm in diameter. The sediment found in the ice cores occurs as mm- to cm-wide bands separated by layers of saline ice. The ice does not grow through the sediment bands

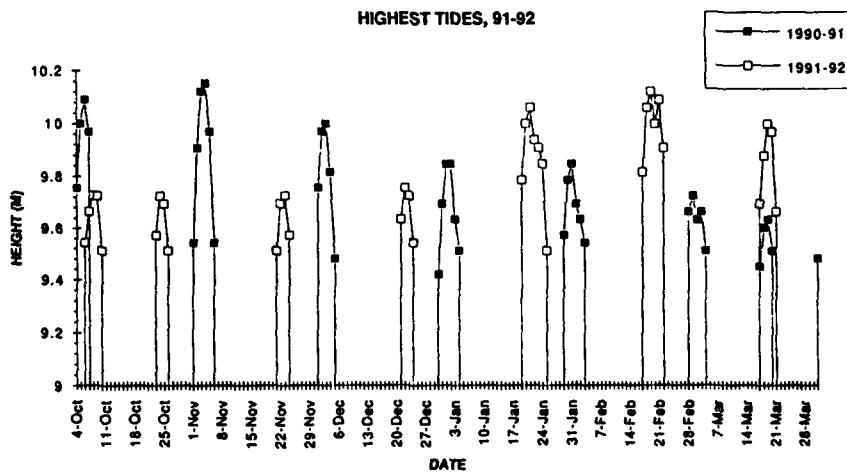
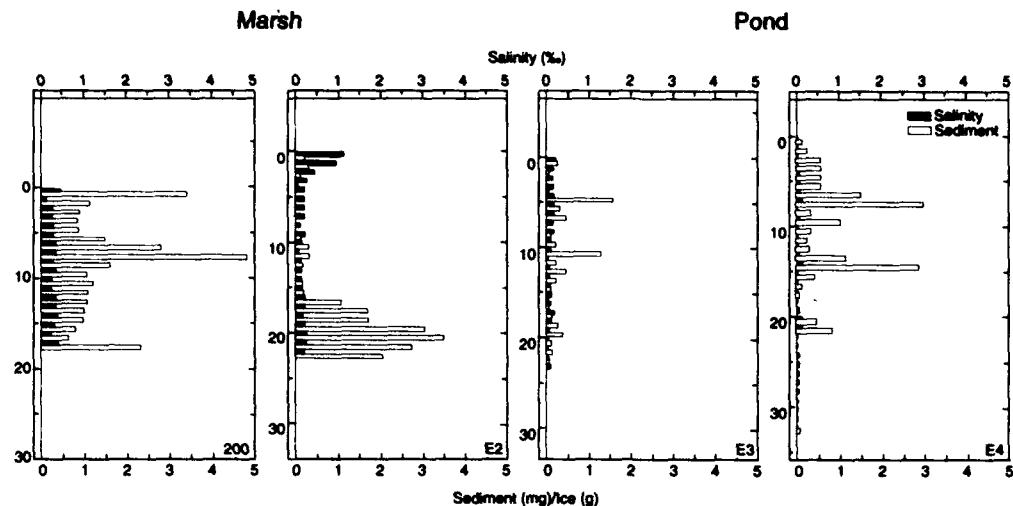


Figure 17. Plot of tides over 9.5 m for the winter months of 1990–91 and 1991–92.



The ice surface elevations of cores 207, E2, and E3 were not recorded the day the cores were collected.

and, because the sediment is associated with high-salinity ice, we infer that it was carried onto the flats by tidal flooding. This is unlike the way sediments become incorporated at Great Bay, New Hampshire, where fast-growing ice entraps sediments entrained in the water column and the sediment is found between crystals in the congelation ice (Meese et al. 1987).

The average sediment content per gram of ice for each core was determined by summing the weight of sediment in each sample and dividing by the sum of the weight of the ice. This value ranges from 0.3 mg/g in the pond to an anomalously high 22.3 mg/g for core 206 adjacent to a distributary chan-

nel (Table 1, Fig. 5). The amount of sediment available for deposition in the spring was estimated by dividing the total sediment weight by the cross-sectional area of the section of core sampled (15 cm^2). The amount of sediment deposited varied widely and there was no clear demarcation among the different salt marsh zones (Table 1). More noticeable is the difference in sediment content between the two winters: less sediment was present in the 1992 cores.

An interesting aside is the presence of bright orange ice, usually near the surface of cores from the bulrush ponds. Under the scanning electron microscope, the orange particulates appear as small

Table 1. The sums of the sediment, salt, and ice weight for each core. The sediment weight (mg/g of ice) and the sediment available for deposition (mg/cm²) are included.

| ERF core no. | Salt weight (mg) | Sediment weight (mg) | Ice weight (g) | Sediment (mg/g ice) | Cross sectional area analyzed (cm ²) | Sediment/cross sectional area of core (mg/cm ²) |
|-------------------|------------------|----------------------|----------------|---------------------|--|---|
| 1991 cores | | | | | | |
| 27 | 134 | 203 | 442 | 0.46 | 16 | 13.53 |
| 31 | 31 | 236 | 65 | 3.63 | 1 | 236.0 |
| 60 | 84 | 1028 | 378 | 2.72 | 15 | 68.53 |
| 62 | 987 | 1337 | 293 | 4.56 | 15 | 89.13 |
| 178 | 482 | 2248 | 202 | 11.13 | 15 | 149.87 |
| 185 | 219 | 967 | 185 | 5.23 | 15 | 64.47 |
| 1992 cores | | | | | | |
| E4 | 24 | 185 | 450 | 0.41 | 15 | 12.33 |
| E3 | 33 | 98 | 303 | 0.32 | 15 | 6.53 |
| E2 | 81 | 243 | 349 | 0.70 | 15 | 16.20 |
| 200 | 134 | 659 | 412 | 1.60 | 15 | 43.93 |
| 202 | 653 | 405 | 292 | 1.39 | 15 | 32.40 |
| 204 | 668 | 486 | 275 | 1.77 | 15 | 32.40 |
| 206 | 679 | 6562 | 294 | 22.32 | 15 | 437.47 |
| 207 | 627 | 885 | 304 | 2.91 | 15 | 59.00 |

flakes on much larger precipitated salt crystals; they do not resemble bacteria or fungi. Energy-dispersive X-ray analysis indicates they are composed of iron. These flakes could be iron oxides made soluble by the low-pH, anaerobic sediments and precipitated in the water column. Alternatively, perhaps the bulrushes cause iron precipitation, as was found for the species *Phragmites australis* (St. Cyr and Crowder 1989).

CONCLUSIONS

Eagle River Flats is a complex estuarine salt marsh, only a small portion of which was studied. The ice cover at ERF varies vertically and spatially with regard to salt and sediment content. The two impurities are correlated, indicating that most of the sediment is deposited by tidal flooding. Generally, the length of the core decreases, and the salt and sediment content increases, with proximity to the river. The presence of salt and sediment lowers the ice's strength, and when the cores are drilled they tend to break along salt and sediment bands.

The ice covering the marshes and mudflats appears to be well-bonded to the underlying sediment. Except in ponds at the periphery of the Flats, we think that the ice is grounded and that tidal flooding occurs on the ice surface, not under it. The craters that pepper the marsh have symmetrical outlines, indicating that large pieces of the underlying sediment are not being plucked out. Large amounts of P₄-contaminated sediments are, therefore, not being removed and transported.

The two winters during which cores were taken differed significantly. The 1991 cores contain evidence for several tidal flooding events before snow began to accumulate. Even within the overlying snow ice, high salinity and sediment layers can be discerned. In contrast, it appears that heavy snowfall early in the 1992 season had the effect of absorbing and limiting tidal flooding. Sediment bands are not seen in the latter cores, probably because the sediment was removed from the floodwater as it was slowed by the snowpack.

Future work should include frequent winter field observations of snow and ice thickness; dye could be used to mark the position of the snow surface at various times so that cores could be com-

pared. The assumption that sediment suspended in the flood waters settles out to form bands marking the base of the flooding event should be tested, as should the effect of different types of wetting (rain, wicked-up water, horizontal flow) on the crystal morphology of snow ice.

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